Polarimetric SAR Image Classification Employing Subaperture Polarimetric Analysis

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Abstract—**Polarimetric SAR image classification remains an important research area. Various methods continue to be developed for specific applications. High-resolution polarimetric SAR systems and advances in computational and data storage capabilities have revived interest in novel polarimetric analysis techniques. Accordingly, subaperture analysis of polarimetric SAR data has received renewed attention. A central assumption of SAR image formation is that individual radar scatterers are stationary; they have no structure and provide a constant reflectivity during the imaging process. However, with increased resolution, and hence fewer scatterers per pixel, the nonstationary response from any given scatterer is more likely to influence total radar backscatter of a pixel. We present a method to assess the polarimetric variability across the full aperture.**

Keywords - classification; subaperture analysis; polarimetric SAR..

I. INTRODUCTION

Polarimetric SAR image classification is an important area of research. Many geophysical applications of polarimetric SAR imagery are being explored in a variety of venues. The goal is to exploit the SAR information in a manner most useful for these applications. Developing new and/or better methods for extracting relevant information from polarimetric SAR datasets remains a critical step in all SAR analysis. Better, or more appropriate, classification techniques improve geophysical parameter estimation, and more generally promote the use of polarimetric SAR data to a wider audience.

With the increased resolution, the nonstationary nature of the polarimetric response becomes readily apparent and a realistic assessment of the nonstationary behavior is possible [1,2]. We focus on azimuth subaperture analysis, employing the subaperture polarimetric image frames as a multiple image dataset for scene classification and analysis.

Two primary sources of nonstationary radar response are temporal variations and view-angle variation (non-spherical scattering characteristics) of the radar backscatter. Temporal variations typically arise from scatterer motion within the scene. Uniform, correlated motion in range of a large number of scatterers results in the classic "train-off-the-tracks" phenomena. Non-uniform and/or azimuth motion of scatterers blurs the full-aperture image and tends to reduce the frame-to-frame correlations between the images formed by azimuth subaperture processing.

View-angle dependencies typically signify manmade radar scatterers and often permit a more robust classification of the scene. One simple type of view-angle variation is broadside flash, *e.g.* the side of a building displays a stronger backscatter at a particular viewing angle. The dominant signal variation is the amplitude of the radar backscatter. In contrast, parallel furrows in plowed fields often show a variation of the scattering mechanism as a function of view-angle. Now the correlations between polarizations vary (not just the amplitudes) [1,3]. Differentiating between polarimetric changes and intensity changes is important for classification.

The cross-correlations amongst the various polarimetric subaperture channels provide additional information for image classification. Therefore, we propose to exploit this information by analyzing the frame-to-frame correlations between the polarimetric covariance matrices derived from each of the subaperture frames.

II. SUBAPERTURE POLARIMETRIC CORRELATIONS

A number of methods are available to analyze polarimetric covariance matrices. Applying these methods directly to sets of polarimetric subaperture frames provides standard brute force approach to subaperture polarimetric analysis. However, these brute force methods tend to obscure the frame-to-frame correlations. Those correlations still exist they are just not so simply displayed.

For concreteness, we assume in the following that the azimuth polarimetric subaperture processing provides a set of five frames. A 3×3 Hermitian covariance matrix defines the polarimetric radar signature of each pixel in each of the subaperture frames. We choose the circular basis for a simpler description of the polarimetry, in principle any basis may be employed, *e.g.* linear or Pauli. The precise details of the azimuth subaperture processing are not important for the following analysis and are not discussed in any detail.

The standard brute force approach is to generate a complex 15×15 Hermitian covariance matrix from the five 3×3 covariance matrices, one from each of the subaperture frames. Generalizing classification techniques that apply to polarimetric covariance matrices to this new 15×15 covariance matrix is straightforward, but not always helpful. As mentioned above the polarimetric correlations between subaperture frames are not transparent and the polarimetric variation across the full aperture is difficult to describe. Here we develop methods that highlight the cross-frame correlations and simplify description of polarimetric variations.

Given a set of five identical subaperture frames the frame-to-frame correlations are highlighted by removing the polarimetric

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14. ABSTRACT

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content from the center frame. Let C_0 denote the 3×3 covariance matrix of center frame. Then eigen decompositions of both C_0 and C_0^{-1} provide the needed simplification.

$$C_0 = \begin{bmatrix} \vec{w}_{0,1} & \vec{w}_{0,2} & \vec{w}_{0,3} \end{bmatrix} \begin{bmatrix} \lambda_{0,1} & & \\ & \lambda_{0,2} & \\ & & \lambda_{0,3} \end{bmatrix} \begin{bmatrix} \vec{w}_{0,1} & \vec{w}_{0,2} & \vec{w}_{0,3} \end{bmatrix}^{\dagger}$$

where the λ's are the eigenvalues and the w's are the corresponding eigenvectors. The inverse, C_0^{-1}, is similarly given by replacing each λ by λ^{-1}. The main point is that C_0 may be post-multiplied by

$$\begin{bmatrix} \vec{w}_{0,1} & \vec{w}_{0,2} & \vec{w}_{0,3} \end{bmatrix} \begin{bmatrix} \lambda_{0,1}^{-1/2} & & \\ & \lambda_{0,2}^{-1/2} & \\ & & \lambda_{0,3}^{-1/2} \end{bmatrix} \text{ and pre-}$$

multiplied by the Hermitian conjugate to produce the identity matrix. Forming a 15×15 block diagonal matrix where each of the blocks is the above 3×3 complex matrix allows analysis of the complete set of subaperture frames. Post- and pre-multiplying by the block diagonal matrix and its Hermitian conjugate reduces the 15×15 polarimetric subaperture covariance matrix to the following matrix

$$\begin{bmatrix}
1 & & 1 & & 1 & & 1 & & 1 & \\
& 1 & & 1 & & 1 & & 1 & & 1 \\
& & 1 & & 1 & & 1 & & 1 & & 1 \\
1 & & 1 & & 1 & & 1 & & 1 & \\
& 1 & & 1 & & 1 & & 1 & & 1 \\
& & 1 & & 1 & & 1 & & 1 & & 1 \\
1 & & 1 & & 1 & & 1 & & 1 & \\
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& 1 & & 1 & & 1 & & 1 & & 1 \\
& & 1 & & 1 & & 1 & & 1 & & 1 \\
1 & & 1 & & 1 & & 1 & & 1 & \\
& 1 & & 1 & & 1 & & 1 & & 1 \\
& & 1 & & 1 & & 1 & & 1 & & 1
\end{bmatrix}$$ that displays the obvious cross-frame correlations. This reduced matrix has only three nonzero eigenvalues. The degeneracy of the remaining twelve eigenvalues highlights the strong correlation between subaperture frames in this example.

This simple example applies (approximately) to the case where the radar scattering is in fact stationary across the full azimuth aperture. Correlations between subaperture frames are obvious strong. And the analysis is simplified because the "polarimetry" is removed by the pre- and post-multiplications.

III. NONSTATIONARY SCATTERING

Non-identical subaperture frames arise either from differences among the eigenvalues, λ's, or changes in the polarimetric scattering mechanisms, *i.e.* the w's. Differences among the eigenvalues change the strength of the scattering but not the polarizations of the scattering mechanisms. In this case, the 15×15 matrix of 1's explicitly shown above, is modified by the ratios of the individual frame eigenvalues with respect the eigenvalues of the center frame. Hence, the 1's may change to other values, but all zeros remain zero. The polarimetric scattering mechanisms are constant across the full aperture,

only their strengths vary. Now the eigen decomposition of this reduced matrix may have fifteen non-degenerate eigenvalues. Note that for this eigenvalue analysis, we have assumed that both the center 3×3 and the total 15×15 covariance matrices are not single-look covariance matrices; they have been either filtered or averaged.

Tracking the changes of the scattering mechanisms is a bit more complicated. Now we need to parameterize the eigenvectors in a meaningful manner. The standard Cloude-Pottier eigenvector parameterization characterizes the average scattering mechanism. In that role, the Pottier-Cloude parameterization works very well. The average scattering mechanism, $\overline{\alpha}$, and orientation angle, $\overline{\beta}$, are easily determined. However, we need a different parameterization, one that characterizes the dominant scattering mechanism, the mechanism associated with the largest eigenvalue, λ_1. Similar to the Pottier-Cloude decomposition, we want to maintain the strong connection between the eigenvector parameters and physical scattering process. Such decomposition has been proposed [4]. A set of rotations and phase adjustments define the eigenvectors expressed in the circular basis. The general form is given below,

$$\begin{bmatrix} \vec{w}_1 & \vec{w}_2 & \vec{w}_3 \end{bmatrix} \equiv \begin{bmatrix} e^{i(\gamma+2\beta)} & & \\ & 1 & \\ & & -e^{i(\gamma-2\beta)} \end{bmatrix}$$
$$\times \begin{bmatrix} \cos\tau & \sin\tau \\ & 1 & \\ -\sin\tau & & \cos\tau \end{bmatrix} \begin{bmatrix} \cos\alpha & -\sin\alpha & \\ \sin\alpha & \cos\alpha & \\ & & 1 \end{bmatrix}$$
$$\times \begin{bmatrix} 1 & & \\ & 1 & \\ & & e^{i\mu} \end{bmatrix} \begin{bmatrix} \cos\nu & & \sin\nu \\ & 1 & \\ -\sin\nu & & \cos\nu \end{bmatrix}$$

As before, the w's are the eigenvectors. The first four parameters, α, β, τ and γ, define the scattering mechanism, orientation angle, helicity and a phase offset of the dominant eigenvector, w_1. These "rotations" rotate w_1 to [0,1,0], in the circular basis [LL, RL, RR]. The two remaining parameters, μ and ν, rotate w_2 and w_3 to [1, 0, 0] and [0, 0, 1], respectively. Unlike the Cloude-Pottier eigenvector decomposition, these parameters are all independent. In the low entropy limit the average scattering mechanism reduces to the dominant scattering mechanism and the four parameters characterizing w_1 are the same for both decompositions, modulo a change of basis. These parameters are all well defined, and meaningful, in the low entropy limit, *i.e.* $\lambda_1 \gg \lambda_2 \gg \lambda_3$.

Ignore the eigenvalues for the time being, the 15×15 reduced covariance matrix describes the set of rotations that rotate the eigenvectors $\begin{bmatrix} \vec{w}_{i,1} & \vec{w}_{i,2} & \vec{w}_{i,3} \end{bmatrix}$ into $\begin{bmatrix} \vec{w}_{0,1} & \vec{w}_{0,2} & \vec{w}_{0,3} \end{bmatrix}$ for all i. These rotation matrices are defined by $\begin{bmatrix} \vec{w}_{i,1} & \vec{w}_{i,2} & \vec{w}_{i,3} \end{bmatrix}^{\dagger} \begin{bmatrix} \vec{w}_{0,1} & \vec{w}_{0,2} & \vec{w}_{0,3} \end{bmatrix}$, for the off-diagonal 3×3 blocks and the product of this matrix with its Hermitian conjugate for 3×3 blocks along the diagonal.

How does this help? The product of the eigenvectors is written in terms of the parameterization in [4] and then the individual terms are easily compared. If the variation of the scattering mechanism varies across the full aperture then one immediately reads-off whether, say, the helicity or orientation angle, *etc.*, has changed and by how much. Similarly, if the scattering mechanism is stationary then the intensity variations are read-off.

Combining both eigenvalues and eigenvectors the frame-to-frame rotation matrices become

$$
\begin{bmatrix} \lambda_{i,1}^{1/2} & & \\ & \lambda_{i,2}^{1/2} & \\ & & \lambda_{i,3}^{1/2} \end{bmatrix} \begin{bmatrix} \overrightarrow{w_{i,1}} & \overrightarrow{w_{i,2}} & \overrightarrow{w_{i,3}} \end{bmatrix}^{\dagger} \begin{bmatrix} \overrightarrow{w_{0,1}} & \overrightarrow{w_{0,2}} & \overrightarrow{w_{0,3}} \end{bmatrix} \begin{bmatrix} \lambda_{0,1}^{-1/2} & & \\ & \lambda_{0,2}^{-1/2} & \\ & & \lambda_{0,3}^{-1/2} \end{bmatrix},
$$

and the diagonal blocks of the block diagonal reduced covariance matrix are the product of this matrix with its Hermitian conjugate. One concern with this formulation is to ensure that the product of eigenvector matrices is diagonally dominant. If not, then a straightforward row or column exchange will make it so. While this correction is not needed mathematically, it does permit easier frame-to-frame comparisons.

IV. POLARIMETRIC SUBAPERTURE CLASSIFICATION

The entire paper has dealt with a rewriting of the 15×15 polarimetric subaperture covariance matrix. A primary reason for this rewriting of the polarimetric subaperture covariance matrix is to simplify the explanation of classification results, *i.e.* why are these two areas different? What has changed? However, these transformations of the covariance matrix do not destroy the under lying Wishart probability distribution. Therefore, our standard Wishart based classification algorithms still apply, but now in a higher dimension. The individual classes found will represent the average scattering characteristics as well as the variations of those observables across the full aperture. The advantage of applying a Wishart classifier at this stage is that one now knows how to interpret the non-stationary results. One can easily determine the variable quantities.

We have generalized the Wishart classifier to handle 15×15 covariance matrices, and will apply the classifier to EMISAR and ESAR polarimetric SAR data. A set of typical scenes will be presented that best highlight the strengths (and weaknesses) of the theoretical analysis presented above. The data displays a range of crop/ground cover types, forests, ocean surface, moving boats and buoys, radio interference, *etc*.

V. DISCUSSION

Modern high-resolution polarimetric SAR systems and advances in computational and data storage capabilities have revived interest in novel polarimetric analysis techniques. Accordingly, subaperture analysis of polarimetric SAR data has received renewed attention. A central assumption of SAR image formation is that individual radar scatterers are stationary; they have no structure and provide a constant reflectivity during the imaging process. However, new polarimetric SAR systems have much improved resolution which a permits realistic assessment of nonstationary behavior.

Additionally, with the increased resolution the nonstationary response from any given scatterer is more likely to influence total radar backscatter of a pixel. Thus with high-resolution SAR systems, nonstationarity becomes more apparent. Here we have focused on azimuth subaperture analysis, employing the subaperture polarimetric images as a multiple image dataset for scene classification.

The cross-correlations amongst the various polarimetric subaperture channels provide additional information for image classification. We exploit this subaperture information by analyzing the frame-to-frame correlations between the polarimetric covariance matrices derived from each subaperture frame.

In the development given above the center frame was used exclusively as a reference against which the other subaperture covariances were compared. There is no inherent reason to use the center frame it this manner. Another reasonable approach would be to use the average covariance, averaged across all subapertures, as the reference against which to compare the individual subaperture covariance matrices.

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